POLARIMETRIC REMOTE SENSING OF SEA ICE

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LONG-TERM GOAL

The long-term goals of this research, in the Sea-Ice Electromagnetics Accelerated Research Initiative Program are to understand the electromagnetic properties of sea ice and their relationship to ice physical and morphological characteristics for developing and validating forward and inverse scattering models of sea ice. For this purpose, accurate polarimetric radar measurements of saline ice under controlled conditions are carried out at microwave frequencies in conjunction with ice characterization measurements to form the experimental basis for the model development and validation.

SCIENTIFIC OBJECTIVES

Polarimetric radar measurements at C band are conducted with the following scientific objectives: (1) identifying volume and surface scattering mechanisms, (2) investigating relative contribution and interactions of volume and surface scatterings, (3) studying effects of temperature and other characterization parameters of sea ice, and (4) effects due to snow, slush, brine, or frost flower cover on sea ice. These are to address the issues in scattering mechanisms in sea ice, development of realistic and tractable models, identification of ice type, and determination of ice deformation characteristics.

APPROACH

The approach is to conduct accurate experiments under controlled conditions, which are designed to provide physical insights into the scattering mechanisms of sea ice and to obtain a data base for validation of forward and inverse models. The experimental results will then be further fed back into the models for iterative refinements of theory and experiments that eventually close the experiment-model loop for understanding of electromagnetic interactions in sea ice. In this perspective, measured data of fully polarimetric signatures of sea ice grown under laboratory conditions together with passive electromagnetic measurements and sea ice characterization data form the complete experimental basis for physical interpretation with sea ice models.

In the effort to relate electromagnetic responses to the physical and morphological properties of sea ice, the quality of measurements is the important factor which requires considerations of data accuracy, calibration, coordination, processing, and reduction as functions of electromagnetic and physical parameters of sea ice.

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WORK COMPLETED

We complete the JPL C-band polarimetric scatterometer data processing, data analyses, compare experimental data physical model calculations, write technical reports and papers, and publish the results for the following studies of sea ice:

1. Diurnal thermal cycling effects on backscatter of thin sea ice;
2. Effects of frost flowers on C-band radar backscatter from sea ice;
3. Evolution in polarimetric signatures of thin saline ice under constant growth;
4. Sea ice backscatter at surface thermal states above the mirabilite crystallization point;
5. Connections between laboratory measurements of sea ice and remote sensing;
6. Thin saline ice thickness retrieval using time series C-band polarimetric radar measurements, in collaboration with Massachusetts Institute of Technology;
7. Inversion algorithm for thickness of saline ice under diurnal thermal cycling conditions, in collaboration with Massachusetts Institute of Technology;
8. Monte Carlo simulation of C-band backscatter from saline ice covered with frost flowers, in collaboration with Massachusetts Institute of Technology;
9. On the estimation of snow thickness distributions over sea ice using the thermal dependence of backscatter change, in collaboration with University of Manitoba;
10. The role of snow on microwave emission and scattering over first-year sea ice, in collaboration with University of Manitoba;
11. Forward models of the electromagnetic properties of sea ice, in collaboration with University of Utah;
12. Recovery of sea ice parameters from microwave inverse models, in collaboration with University of Utah; and
13. Evolution of electromagnetic signatures of sea ice from initial formation through the establishment of thick first-year ice, in collaboration with University of Washington.

RESULTS

We summarize the results in the following sections according to the work listed in the last section:

1. Measured sea ice backscatter revealed substantial diurnal variations up to 6 dB with repeatable cycles in synchronization with the temperature cycles and the emission modulations. The diurnal cycles in backscatter indicate that the dominant scattering mechanism related to thermodynamic processes in sea ice is reversible. A diurnal backscatter model based on sea ice electrodynamics and thermodynamics explains the observed diurnal signature. This work shows that diurnal effects are important for inversion algorithms to retrieve sea ice geophysical parameters from remote sensing data acquired with a satellite SAR or scatterometer. on sun-synchronous orbits;
2. C-band radar measurements of frost flowers on sea ice show that the crystals in frost flowers have little impact on the backscatter, while the underlying slush patches yield a backscatter

increase of 3-5 dB over that of bare ice. The laboratory results suggest that this relative backscatter increase of approximately 5 dB can be used as an index to mark the full aerial coverage of frost flowers;

3. A strong increase of 6-10 dB is observed in the backscatter as the ice grows from 3 cm to 11.2 cm in thickness. Ice characteristics and processes suggest that the large enhancement in backscatter relates to the interconnection and increase in the size of brine inclusions during the desalination process;

4. Measured backscattering coefficients sigma_hh and sigma_vv are well correlated to and follow exactly the same trend of the temperature variations. The change in the backscatter is large and varies as much as 10 dB or 1 order of magnitude between cold and warm cases. In these cases, the ice surface temperature is above the mirabilite crystallization point (-8 deg C);

5. We suggest that laboratory backscatter signatures should serve as bounds on the interpretation of remote sensing data. We examine these bounds from the perspective of thin ice signatures, the effect of temperature, and surface processes such as frost flowers and slush on these signatures. Controlled experiments also suggest new directions in remote sensing measurements. The potential of polarimetric radar measurements in the retrieval of thickness of thin ice is discussed. In addition to the radar results, we discuss the importance of low-frequency passive measurements with respect to the thickness of thin ice;

6. The inversion algorithm uses a parametric estimation approach where the radiative transfer equation is used as the direct scattering model to calculate the backscattering signatures from ice medium, and the Levenberg-Marquardt method is employed to retrieve ice thickness iteratively. Additional information provided by the saline ice thermodynamics is applied to constrain the electromagnetic inverse problem to achieve a reasonably accurate reconstruction. The inversion results using this algorithm and the data from CRRELEX 93 experiment are compared. The accurate thickness retrieval suggests the potential usage of this algorithm for satellite remote sensing of sea ice and other geographic regions;

7. In the case of sea ice growth under diurnal thermal cycling conditions, reasonable results for ice thickness inversion can be obtained with the method described in the last paragraph when the sea ice thermodynamics is accounted for;

8. We carried out Monte Carlo simulation of C-band backscatter from saline ice covered with frost flowers. Frost flowers are modeled as slush patches of a high dielectric constant due to the high salinity. Calculated results compare well with experimental data and the drop in backscatter at the surface salinity doubling is explained;

9. We introduce an approach to estimating snow thickness on first year sea ice. We use data from the Seasonal Sea Ice Monitoring and Modeling Site (SIMMS) located in the Canadian Archipelago. Results show that the thermodynamics of the snow cover affect the surface dielectrics through the control that brine volume exerts on the complex dielectric constant. The effect is subtle and specific to certain ranges of sea ice thickness, salinity and surface roughness. We describe the phenomenon responsible for this effect using dielectric mixture models coupled to a one-dimensional thermodynamic model. We validate the physical principles using in situ field data. We then explore the capabilities of synthetic aperture radar

(SAR) in estimating snow thickness distributions under these specific conditions using both observed (ERS-1) and modeled microwave scattering;

10. Backscattering is seen to increase dramatically with increasing grain size. Results indicate that at 5.3 GHz volume scattering is important. It is lower than surface scattering when there is no snow and becomes higher than surface scattering when there is snow. Indirect effects of snow on microwave scattering and emission are driven by the thermodynamics of the snow/sea ice system and the role that thermal diffusivity and conductivity play in the definition of brine volumes at the ice surface and within the snow volume;
11. The analytic wave model for sea ice scattering accounts for the thermodynamic phase distribution of constituents in sea ice, orientation distribution of crystallographic c-axes, non-spherical geometry of brine pockets and other inhomogeneities, anisotropy of columnar ice, thickness distribution in thin ice, brine layer and snow cover, roughness at sea ice interfaces, and melt hummocks. The model compares well with measured data in general and provides physical insights into sea ice signatures observed by remote sensors in order to interpret the signature behavior and to assess the retrieval of important geophysical parameters of sea ice;
12. We demonstrate the use of neural network to invert for thickness of young sea ice with multifrequency polarimetric microwave data. The approach is to retrieve the ice thickness by using the analytic wave theory model to train the neural network to match measured data in the selection of the ice thickness. We use the multi-layer perceptron with a modified backpropagation algorithm to improve the convergence rate and accuracy. Physical interrelations of physical parameters governed by sea ice physics under typical Arctic winter environmental conditions are utilized to restrict the solution space to avoid extraneous solutions and shorten the required computation time. The neural network is applied to JPL polarimetric SAR data to obtain ice thickness results of young sea ice in refrozen new leads in the Beaufort sea; and
13. Time series of young sea ice signatures, such as microwave emissivity, radar backscatter, and spectral albedo in the visible and infrared, have been measured at successive stages in the growth of sea ice both under laboratory conditions and in the field. These observations have been accompanied by studies of the structural properties and near surface characteristics that influence the interaction between radiation and the ice. This has built up a consistent data set that covers essentially all phases of the development of the different types of first-year sea ice identified by WMO from open water and new ice through thick first-year ice.

IMPACT/APPLICATION

The data collected with the polarimetric C-band radar and the sea ice models address the scientific objectives presented in Section 2. The C-band polarimetric radar results are particularly suitable for applications to many present and future remote sensing radars such as the JPL airborne SAR, Spaceborne Imaging Radar, European Remote Sensing Satellites (ERS-1 and ERS-2), and Canadian RADARSAT, all operating at C band. The research in this project focuses on the microwave regime of the electromagnetic spectrum especially at C-band frequency, which will facilitate the analysis of airborne and spaceborne data to identify ice types and to retrieve physical parameters for global monitoring of sea ice. Specific applications to satellite SAR remote sensing are discussed in the paper “Laboratory Measurements of Sea Ice: Connections to

Microwave Remote Sensing" by Kwok et al., submitted for publication in the IEEE Transactions on Geoscience and Remote Sensing.

TRANSITIONS

The C-band polarimetric scatterometer developed in this program for sea ice polarimetric backscatter measurements can be used to study other geophysical media. The scattering model for sea ice can be modified to calculate polarimetric backscatter from other geophysical media.

RELATED PROJECTS

The following projects are a direct outgrowth of research funded under the core program of the Space and Remote Sensing Program:

1. Collaboration with Cold Regions Research and Engineering Laboratory to correlate radar data with sea ice physical characterization data;
2. Collaboration with School of Oceanography, University of Washington to carry out experiments to investigate effects of frost flowers on polarimetric radar backscatter;
3. Collaboration with Massachusetts Institute of Technology to study ice thickness inversion and to model backscatter from frost flowers;
4. Collaboration with Department of Atmospheric Sciences, University of Washington to compare active and passive microwave signatures of sea ice growth;
5. Collaboration with Department of Geography, University of Manitoba to analyze effects of snow cover on microwave radar backscatter; and
6. Collaboration with both modeling and experimental groups in the Sea-Ice Electromagnetics Accelerated Research Initiative Program to develop and validate forward and inverse sea ice models.

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